APPENDIX C

Acoustics Memorandum

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Memorandum

To: Louise Flynn, Assistant Project Manager

From: Michael T. Williams

Date: 31 October 2002

Re: Acoustic Appendix

Ms. Flynn, attached is an appendix that includes (1) Acoustic Concepts and Terminology, (2) Underwater Noise Propagation, (3) Zones of Influence, (4) Marine Mammal Hearing, and (5) Underwater Noise and Acoustics Environment. Please consider this text as supplemental to the other sections of the EIS to provide an in depth discussion of acoustics in order for the reader to gain a better understanding of the concepts discussed in the Soundscape, Threatened and Endangered Animals, and Marine Mammals sections.

1.0 ACOUSTIC CONCEPTS AND TERMINOLOGY

1.1 INTRODUCTION AND SCOPE

This section contains an introduction to acoustic concepts and terminology to aid non-acousticians in understanding the terms and techniques used in this report. It is based on a longer presentation given by Charles R. Greene, Jr. in Chapter 2 of *Marine Mammals and Noise* (Richardson et al. 1995). The scope of the material presented here is focused on acoustic principles and terminology used in this report. For a broader coverage of general acoustic concepts the reader should refer to *Marine Mammals and Noise* and to *Principles of Underwater Sound* (Urick 1983). Technical terms are identified by an underline when first described.

1.2 SOUND MEASUREMENT UNITS

1.2.1 Basic Units

Sound is produced when waves of vibrational energy travel through air or water as oscillations of the fluid particles to exert tiny push-pull pressures on our eardrums or transducers. Transducers (hydrophones or microphones) act as electronic ears, converting pressure waves to electronic signals. The frequency of the oscillation or vibration is measured in cycles per second or hertz.(Hz) The pitch of a sound as perceived by a human is directly related to frequency. Humans are often said to hear sounds ranging from 20 to 20,000 Hz. However, for most individuals the actual range of useful sensitivity is narrower. A tone, sometimes called a pure tone, involves a sinusoidal oscillation at a specific frequency. Frequency is the reciprocal of the oscillation period, which is the time required for one oscillation. The wavelength (•) of a periodic sound is the length of the fundamental oscillation in the propagation medium. To a physical acoustician, sound is a mechanical wave motion propagating in an elastic medium at a sound velocity (c) that depends on the relative compressibility of the medium. The wavelength of a single tone is related to its frequency by the equation:

$$\bullet = c/f \qquad (1.1)$$

Some fluctuations in fluid pressure are commonly called sounds even though they cannot be heard by humans. Ultrasonic frequencies are too high to be heard by humans (>20,000 Hz); infrasonic sounds are too low to be heard (<20 Hz). Many animals (e.g., dolphins, bats, and dogs) can detect certain ultrasounds. Some animals, including elephants, pigeons, and probably some baleen whales, can detect certain infrasounds.

A useful model of the acoustic process is the 'source-path-receiver'model. This model includes
a source of sound with specific frequency and temporal characteristics,
the sound transmission path(s) that changes sound characteristics as the sound propagates
and
a receiver with specific detection capabilities.

For example, consider a whale swimming near a ship: the ship is a source of underwater sound, the water (including surface and bottom) is the path from source to whale, and the whale is the receiver.

Source characteristics include variability over time (transient versus continuous), and sound intensity distribution in frequency (source level spectrum*)*. Transmission refers to the propagation of sound through the air, water, or bottom from a source to a receiver. The transmission path is the route from source to receiver, The path may include various combinations of air, water, or bottom materials. The path often is not a straight line. Multiple transmission paths (multipaths) occur when sound reflects from surfaces along the path, such as the surface and (in underwater sound transmission) the bottom. Rough surface or bottom features cause sound to be scattered, and some underwater sound impacting the bottom is absorbed. Refraction (ray bending) can be important in either under-water or airborne sound transmission. In this report the receivers of interest are marine mammals. Important receiver characteristics include an animal's hearing sensitivity to sounds at different frequencies and its responsiveness to different types and levels of sounds.

The energy or acoustic intensity transmitted by sound waves is rarely measured directly but is often discussed. It is important because it is a fundamental measure of propagating sound. It is defined as the acoustical power per unit area in the direction of propagation; the units are watts/m^2. The intensity, power, and energy of an acoustic wave are proportional to the average of the pressure squared (mean square pressure). Acoustics researchers often refer to intensities or powers, but they derive these from pressures squared. Measurement instruments (and ears) normally sense pressure, from which intensity or power is computed. This practice is legitimate for measurements in the same medium (i.e., in water or in air), where constants of proportionality between intensity or power and pressure are the same. For most sound receivers sound pressure is measured in micropascals (• Pa). A pascal is a standard unit of pressure in the SI system of units. One pascal is the pressure resulting from a force of one Newton exerted over an area of one square meter.

In presenting sound measurements, acousticians use ratios of pressures, or pressures squared, requiring adoption of a standard reference pressure for use in the denominator of the ratio. The reference pressure for underwater sounds is 1 • Pa (Table 1.1). For airborne sound it is conventional to use 20 • Pa as the reference pressure—the approximate threshold of human hearing at 1 kHz (Table 1.1).

The human ear is capable of responding to a very wide range of sound intensity levels – a factor of 10^{13}. It spans this range by means of a logarithmic response, therefore acousticians have adopted a logartithmic scale for sound intensity denoted in decibels. In decibels, the intensity level of a sound of intensity I is given by equation (1.2):

Intensity Level (dB) = $10 \log (I/I_0)$ (1.2)

where I_0 is the reference intensity, 10^{-12} W/m^2 . Because intensity is proportional to pressure squared, the sound pressure level (SPL) of a sound of pressure P is given by

Sound Pressure Level (dB) = $20 \log (P/P_0)$ (1.3)

where P is the reference pressure, e.g., 1 • Pa. The phrase "sound pressure level" implies a decibel measure and that a reference pressure has been used as the denominator of the ratio.

In summary, when studying underwater sound, we usually measure pressure, not intensity. The reference pressure for underwater sounds is one micropascal (• Pa).

Pulsed sounds usually should be measured in terms of their energy, not just their pressure or power. Energy is proportional to the time integral of the pressure squared. Thus, sound energy is proportional to and may be described in terms of • Pa^2–s (micropascal, squared, for one second). Airborne impulsive sounds are usually measured on an energy basis, integrating the squared instantaneous sound pressure over the pulse duration and adjusting the resulting level to a reference one sec duration to obtain the Sound Exposure Level (SEL). A frequency-dependent filter approximating the human hearing curve (A-weighting) is used unless otherwise stated (ANSI 1994). The energy measurement technique, without A-weights, is sometimes applied in underwater acoustics, but rarely in studies of underwater noise versus marine mammals. Better standardization and reporting of measurement methods for pulsed underwater sounds are urgently needed to permit meaningful comparisons among studies.

1.2.2 Sound Spectra

Sound spectra are important because we use them to describe the distribution of sound power as a function of frequency. An animal's sensitivity to sounds varies with frequency, and its response to a sound is expected to depend strongly on the presence and levels of sound in the frequency band (range of frequencies) to which it is sensitive.

A sound waveform represents the amplitude variations of the sound with time. Sound from some sources has power distributed over a wide range of frequencies. Some sound components may be periodic, consisting of a repeated waveform whose power is concentrated at specific frequencies. The waveform of a pure tone is a simple sinusoid. However, other components of sounds are continuously distributed across frequency. Such sound may have a hissing quality at high frequencies or a rumbling quality at low frequencies. The waveforms of these more complex sounds are erratic.

To describe continuously distributed sounds, acousticians use the concept of power density spectrum. This is a graph plotting power per unit frequency versus frequency. Because measurements are usually in terms of pressure rather than power, a more common graph is the sound pressure density spectrum—the mean square pressure per unit frequency, in • Pa^2/Hz (e.g., Fig. 1.1).

1.2.3 Levels of Tones

A tone is a sinusoidal waveform for which all power is at a particular frequency. Tones originate from rotating or oscillating objects. For example, something that rotates at 3000 rpm (50 times/s) likely will create a tone at 50 Hz. There may be additional tones (harmonics) at integer multiples of this fundamental frequency (100, 150 .Hz). For a multibladed propeller or turbine, the blade rate (rotation rate per second times number of blades) is often the fundamental frequency of a harmonic family of tones.. The pure tone has all its power at one frequency. As filter bandwidth decreases, the output from the filter containing the tone remains constant.

1.2.4 Octave and 1/3-Octave Levels

Sound pressure density spectrum levels, representing mean square sound pressure per unit of frequency, can be integrated over a range of frequencies (band) to obtain the mean square pressure expected in the band.

To facilitate comparison of sources with different ouput power and frequency content, two types of proportional bandwidth filters have been adopted as standards: octave band for noise-control engineering applications, and one-third octave band for hearing response related applications. In each case, filter bandwidth is proportional to filter center frequency. An octave is a factor of two in frequency. For example, middle C on the music scale is at 262 Hz; the next higher C on the scale, an octave higher, is at 524 Hz. The bandwidth of a 1-octave band is 70.7% of its center frequency and the bandwidth of a 1/3-octave band is 23% of its center frequency. Standard center frequencies (in Hz) for adjacent ½-octave bands include the following:

50 63 80 100 125 160 200 250 315 400 500 Hz

plus other frequencies lower or higher by factors of 10. Sound levels are often presented for 1/3 -octave bands because, in humans and some animals, the effective filter bandwidth of the hearing system is roughly 1/3 octave.

1.3 TERMS DESCRIBING SOUND SOURCES

1.3.1 Temporal Properties

A sound may be transient, of relatively short duration having an obvious start and end, or it may be continuous, seeming to go on and on. Transient underwater sounds include impulsive transient sounds from explosions, airguns, pile drivers, and sonars. An explosion produces a single transient sound, but airguns, pile drivers, and many sonars produce repeated transients. Sound from a fixed, ongoing source like an operating drillship is continuous. However, the distinction between transient and continuous sounds is not absolute. Sound emitted from an aircraft or a ship underway is continuous, but it is transient insofar as a stationary receiver is concerned. Also, many sounds are not purely transient or purely continuous even at the source. For example, on a drillship, generators and pumps operate essentially continuously, but there are occasional transient bangs and clanks from various impacts during operations.

In describing a transient sound it is useful to present the peak level as well as some description of how the sound varies with time— its waveform. The peak level may be described as being a particular pressure, or as a mean square pressure averaged over a relatively short interval. The latter approach allows more reasonable comparisons with mean square pressures of continuous sounds. When transient sounds are so short as to be impulsive, they are best described in terms of their energy levels (Section 1.2.1) and energy density spectra. Some transient sounds, like airgun impulses, occur periodically. For such sources it is also helpful to describe the duty cycle, or the fraction of time during which the transients are significant.

A continuous sound or slow transient may be described by its mean square pressure and its mean square pressure density spectrum, for some defined averaging time. The latter shows the distribution of sound power versus frequency (e.g., Fig. 1.1). It may also be useful to show the corresponding levels in various 1/3-octave and 1-octave bands (e.g., Fig. 1.2).

1.3.2 Amplitude Properties

Source level is defined as the pressure level that would be measured at a standard reference distance (e.g., 1 m) from an ideal point source radiating the same amount of sound as the actual source being measured. This concept is necessary because sound measurements near large, distributed sources, like ships, depend strongly on source size and measurement location, and are difficult to relate to levels measured far away. Such near-field measurements are generally lower than would be obtained at the same distance from a point source radiating the same amount of energy. The concept of source level introduces the dimension of distance into the description of sound. In general, sound level decreases with increasing distance from the source. To compare different sound sources, it is necessary to adopt a standardized reference distance at which source levels will be determined. Normally, field measurements are made at distances larger than the standard reference distance, beyond the near field. Source level is determined by taking into account the known or expected change in level (propagation loss) between the reference and actual distances. For underwater sounds, a reference distance of 1 m (or 1 yard in older reports) is usually cited (and is used in this report). However, in some reports on ship noise the reference distance may be 100 m or 100 yards. In any case, source level is estimated by adjusting the measured level to allow for transmission loss between a standard reference range and the range where the sound was measured. Only in this way can source levels of various sounds be compared.

1.4 TERMS DESCRIBING SOUND PROPAGATION

Discussions of sound propagation include two equivalent terms: transmission loss (TL) and propagation loss. Chapter 1 discusses this topic in greater detail, but some introductory material is necessary to understand parts of that and other chapters. Conceptually, a sound wave traveling from point A to point B diminishes in amplitude, or intensity, as it spreads out in space, is reflected, and is absorbed. If the source level (at 1 m) is 160 dB re 1 • Pa-m, the received level at range 1 km may be only 100 dB re 1 • Pa; in this case TL is 60 dB. TL is generally expressed in dB, representing a ratio of powers, intensities, or energies of a sound wave at two distances from the source. The distance at which the denominator measurement was taken is the reference distance for TL. Because dB scales are logarithmic, and log (ratio) equals log (numerator) minus log (denominator), TL can be expressed as the difference, in dB, between the levels at the two distances. Strictly speaking, TL is a positive quantity, but it is plotted downward, as in Fig. 1.3. A person viewing a TL graph can visualize the way in which a sound diminishes with increasing distance.

A major component of transmission loss is spreading loss. From a point source in a uniform medium (water or air), sound spreads outward as spherical waves. Spherical spreading implies that intensity, or the mean square pressure, varies inversely with the square of the distance from the source. Thus, TL due to spherical spreading is given in dB by 20 log (R/R_0) where R_0 is the reference range, normally 1 m. With spherical spreading, sound levels diminish by 6 dB when the distance is doubled, and by 20 dB when distance increases by a factor of 10 (Fig. 1.3).

Cylindrical spreading sometimes occurs when the medium is non homogeneous. In shallow water, sound reflects from the surface and bottom. At some distance from the source that is long compared to water depth, various reflected waves combine to form a cylindrical wave. Such a wave may be imagined by picturing a short tuna fish can. The top and bottom of the can correspond to the water surface and ocean bottom, and the curved outer surface is the cylindrical wavefront. In some situations (Chapter 1), a near-cylindrical wave can also form as a result of refraction or ray-bending. With cylindrical spreading, the sound intensity varies inversely with distance from the source. With cylindrical spreading, sound levels diminish by 3 dB when distance doubles, and by 10 dB when distance increases 10-fold. Thus, levels diminish much more slowly with increasing distance with cylindrical than with spherical spreading (Fig. 1.3).

Sound rays are refracted (bent) when sound speed changes along the ray path. *Refraction* is common in the atmosphere and the ocean when temperature varies with height above ground or depth in the ocean; temperature has a major influence on sound speed. Refraction of sound rays can result in convergence zones, which are regions of focused rays and higher sound levels; and shadow zones, which are regions of very low sound level.

As sound travels, some power is absorbed by the medium, giving rise to absorption losses. Such losses vary linearly with distance traveled, and absorption loss can be described as x dB/km. Absorption losses depend strongly on frequency, becoming greater with increasing frequencies. Scattering losses also vary linearly with distance, but result from different physical mechanisms. These losses are in addition to the spherical, cylindrical, or other spreading losses previously mentioned (e.g., Fig. 1.3B).

The terms phase, phase difference, relative phase, and phase angle can be used in comparing two periodic waveforms with the same period. For example, sound components from one source that arrive at a given point via two different propagation paths may differ in phase. Phase refers to the difference in time, or the offset, between two waveforms. If the difference equals the period, or any integer multiple of the period, the two waveforms look the same and the phase difference is zero. Thus, it is possible to describe phase as an angle in the range ± 180°. For example, if phase difference is 1/4 of the period, phase angle is ±90°. The sign depends on whether the waveform of interest is "ahead of' (leads +) or "behind" (lags -) the reference waveform. For continuous waveforms that are random or nonperiodic, the phase concept generalizes to one of time delay, describing the time offset of a waveform and its replica.

1.5 TERMS DESCRIBING AMBIENT NOISE

Ambient noise is the background noise. There is no single source, point or otherwise. In the ocean, ambient noise arises from wind, waves, surf, ice, organisms, earthquakes, distant shipping, volcanoes, fishing boats, and more. At any one place and time, several of these sources are likely to contribute significantly to ambient noise. In the source-path-receiver model, ambient noise is present in the medium (water or air) along the path, and it is present at any receiver location. Ambient noise varies with season, location, time of day, and frequency. It has the same attributes as other sounds, including transient and continuous components, tones, hisses, and rumbles. It is measured in the same units as other sounds. However, in measuring ambient noise, it makes no sense to use a reference distance from the "source", as there is no one source.

1.6 TERMS DESCRIBING SOUND RECEPTION

Sounds can be received by animals' ears and instruments such as hydrophones and microphones. Hydrophones and microphones are transducers that transform received acoustic pressures into electrical voltages or currents, which may be amplified and conditioned for application to meters, tape recorders, speakers, or earphones. These transducers are characterized by their sensitivities, which vary with frequency, by the electrical noise they add to received sound, and by their distortion properties. Hydrophone sensitivities generally are described in volts per micropascal or in dB re 1 V/• Pa.

Animals, including people, have complicated sound reception capabilities. We introduce a few key terms here. More terminology related to hearing is given in Chapter 8 of *Marine Mammals and Noise* (Richardson *et al*. 1995) and Section 4 of this memorandum. The absolute auditory threshold of an animal is the minimum received sound level at which a sound with particular frequency and other properties can be perceived in the absence of significant background noise. Threshold and auditory sensitivity are inversely related. In other words, an animal can hear a fainter sound if the threshold is low than if it is high, and vice versa.

Auditory thresholds vary with frequency. A graph of thresholds versus frequency, called an audiogram, typically is U-shaped. Thresholds generally are high (poor sensitivity) at low frequencies. From there, thresholds generally diminish (improved sensitivity) with increasing frequency, up to some frequency range of optimal sensitivity (best frequency). Above that range, thresholds increase (deteriorating sensitivity) with a further increase in frequency. The "best frequency" varies from one species to another. Section 8.2 in Richardson *et al*. (1995) includes underwater and in-air audiograms of all marine mammal species for which audiograms have been measured; the human in-air audiogram is also shown (Fig. 8.3).

The terms critical ratio and critical band deal with the audibility of a pure tone in the presence of background noise. People and animals have varying abilities in this regard. The critical ratio is the ratio of the level of a barely audible tone to the spectrum level of background noise at similar frequencies. Because of the logarithmic nature of dB scales, a critical ratio can be derived by subtracting the spectrum level of the background noise from the tone level. For example, if a tone must be 100 dB re 1 • Pa to be detected with background noise of 80 dB re 1 • Pa at similar frequencies, the critical ratio is 20 dB (i.e., 100 minus 80). Critical ratios tend to increase with increasing frequency.

Critical bands can be defined in different ways, but in general the critical band around a given frequency is the band within which background noise affects detection of a sound signal at that frequency. Background noise at frequencies outside the critical band has little effect on detection of a sound within that band unless the noise level is very high. Critical bands are often roughly 1/3 octave wide. Hence, it is often useful to summarize man-made noise and ambient noise on a 1/3 octave basis. The process by which background noise may prevent detection of sound signals at nearby frequencies is called masking.

2.0 Underwater Noise Propogation

2.1 Introduction

This section is included to provide an introduction to sound propagation for non-acousticians. It is based on a longer summary of sound propagation principles contained in Chapter 4 of *Marine Mammals and Noise* (Richardson et al. 1995). The scope of the material presented here is concerned primarily with the acoustics of the Glacier Bay environment and focuses on underwater sound propagation in shallow water with a brief discussion of airborne sound propagation and transmission of airborne sound into water. For a more complete discussion, including deep water sound transmission and theoretical aspects of sound propagation, the reader is referred to *Marine Mammals and Noise*, and to *Principles of Underwater Sound* (Urick 1983).

The audibility or apparent loudness of a noise source is determined by the radiated acoustic power (source level), the propagation efficiency, the ambient noise, and the hearing sensitivity of the subject species. Noise levels produced by human activities in underwater and terrestrial environments are determined not only by their acoustic power output but, equally important, by the local sound transmission conditions. A moderate-level source transmitting over an efficient path may produce the same received level at a given range as a higher-level source transmitting through an area where sound is attenuated rapidly, that is, over a "lossy" path. Likewise, a given noise source operating in different areas, or in the same area at different times, may be detectable for greatly varying distances, depending on regional and temporal changes in sound propagation conditions among other factors. In deep water, depth variations in water properties strongly affect sound propagation. In shallow water, interactions with the surface and bottom have strong effects.

As a result, the zone of acoustic influence for a given source of man-made noise can vary in radius 10-fold or more, depending on operating site and depth, and on seasonal changes in water properties. Hence, sound transmission measurements, analyses, and model predictions are necessary to estimate the potential radius of acoustic influence of noisy human activities.

Site-specific sound propagation data are often lacking when a potentially noisy activity is planned. It is often not feasible to obtain in situ sound transmission measurements to estimate how intrusive the new noise will be. However, predictions can often be made even without site-specific propagation data. Predictions are based on propagation models developed for both airborne and underwater sound. These models provide procedures for estimating the received noise level as a function of distance, assuming that the source level and characteristics are known. These propagation models may be purely theoretical, based on physical principles; or semi-empirical, using both physical principles plus field measurements.

Model predictions can be useful for planning and for preparing environmental impact statements, but it is advisable to obtain relevant empirical data as well. This is important because of the highly variable and site-specific nature of underwater sound transmission, especially in shallow water, and of airborne sound transmission near the ground.

This section describes some sound propagation concepts relevant to noise impact prediction. We provide a brief review of theoretical aspects; shallow water, and airborne sound transmission; and air-to-water transmission. Equations are included where useful for clarity, but the reader should refer to the references described previously for a more detailed theoretical treatment of the topics presented here.

2.2 Theoretical Aspects

In a uniform medium with no nearby boundaries and no absorption loss, sound from an omnidirectional source spreads uniformly outward with a spherical wavefront. Intensity decreases as the area of the wavefront expands. At distances that are large compared with the source dimensions (far field), sound intensity varies inversely as the square of range from the acoustic center of the source. Since sound intensity is proportional to sound pressure squared, sound pressure is inversely proportional to range. In logarithmic terms, this is called a 20 log R spreading loss or spherical spreading:

$Lr = L_s - 20 \log R$

where Lr is the received level in dB re 1 • Pa (underwater) or dB re 20 • Pa (in-air),

L_s is the source level at 1 m in the same units, and R is the range in m.

When sound becomes trapped in a sound duct between horizontal refracting or reflecting layers, it is constrained to spread outward cylindrically rather than spherically. Cylindrical spreading also occurs when sound is trapped between the surface and bottom in shallow water. In these cases, sound intensity decreases in proportion to the increase in area of the expanding cylindrical wavefront. As a result, sound intensity varies inversely as the range from the source (i.e., as 1/R), in contrast to the $1/R^2$ that applies with spherical spreading. Sound pressure varies inversely as the square root of range (i.e., as $1/R^{0.5}$), in contrast to the 1/R that applies with spherical spreading. This is the 10 log R spreading loss of cylindrical sound transmission:

$L_r = L_s - 10 \log H - 10 \log R$

where H is the effective channel depth. The "- 10 log H" term is related to the fact that cylindrical spreading does not begin at the source; spreading is usually more or less spherical from the source out to some distance (approximately equal to the water depth), and then may transition to cylindrical. Sound attenuates much more rapidly with increasing distance with spherical (20 log R) than with cylindrical (10 log R) spreading (Fig. 1.3). A given source can be heard farther away when there is cylindrical spreading along much of the path from source to receiver.

Simple spherical or cylindrical spreading are important theoretical concepts and apply at least approximately to many real-world situations. However, the ocean is not a uniform medium. Variations in temperature and salinity with water depth affect the rate of propagation loss. The speed of sound increases with increasing temperature, salinity, and pressure. This results in distortion of the wavefront as it propagates. This distortion is equivalent to bending (refraction) of the sound rays that trace the paths of points on the wavefront. Refraction causes rays to be bent toward the direction of slower sound speed, since the portion of the wavefront traveling in the region of higher sound speed advances faster than the remaining portion. Refraction is a dominant feature of sound transmission in both deep and shallow water. Variation of sound speed with depth controls the ray paths. As a result, the decrease of sound intensity with range is influenced not only by spreading loss but also by concentration or reduction in the ray density due to refraction. In the current application the gradients are those of the summer season in Glacier Bay so the effects of seasonal changes on transmission loss will not be discussed in detail.

In shallow water with an absorptive bottom the 10 Log R spreading loss of cylindrical reflection is not appropriate because energy is lost by bottom absorption and scattering. In regions where the bottom reflection loss for sound rays is proportional to the angle of incidence with the bottom a 15 Log R spreading loss is developed, but often there are variations in the transmission path properties that result in a multistage range-dependent spreading loss characteristic. This is discussed in more detail in the next subsection.

2.3 Shallow Water Sound Propagation

Sound transmission in shallow water is highly variable and site-specific because it is strongly influenced by the acoustic properties of the bottom and surface as well as by variations in sound speed within the water column. As in deep water, variations in temperature and salinity with depth cause sound rays to be refracted downward or upward. Refraction of sound in shallow water can result in either reduced or enhanced sound transmission. With upward refraction, bottom reflections and the resulting bottom losses are reduced; with downward refraction the opposite occurs. Thus, sound transmission conditions in continental shelf waters and bays can vary widely.

The many environmental factors that influence shallow water sound transmission make it difficult to develop adequate theoretical models. One must combine theory with site-specific empirical data to obtain reliable propagation predictions. Low frequency sounds do not propagate well in shallow waters due to the long wave lengths, whereas high frequency sounds propagate relatively well. In many cases, however, the bottom consists of water-saturated sediment and does not reflect all the sound energy. In these conditions, propagation of low-frequency energy extends downward into the bottom material. If the composition and layer structure of the bottom are known, or can be estimated, this information, when incorporated into the modal analysis procedure, permits calculation of shallow water sound transmission losses with good accuracy.

To accommodate the variability of real-world data, semi-empirical propagation models have been designed for application to shallow water. It is possible to make reasonable propagation predictions from simple formulas of these types if sound speed is nearly independent of water depth and if the bottom either is flat or slopes uniformly and gradually (Weston 1976). Weston's formulas divide the shallow water transmission path into four regions: a spherical spreading region near the source (20 Log R); a transitional, cylindrical-spreading region where bottom- and surface-reflected rays contribute more energy than the directly transmitted rays (10 log R); a grazing angle dependent, "mode-stripping", region (15 Log R); and a "lowest-mode" cylindrical spreading region (10 Log R). Weston's formulas have been modified by P.W. Smith, Jr. (Malme et al. 1986), and incorporated into a short computer program (Weston/Smith Model) that calculates transmission loss when given parameters of frequency, water depth at the source, bottom slope, and two parameters describing the bottom reflection loss.

2.4 Absorption and Factors Affecting Spreading Loss

Several additional factors can have important influences on sound propagation in both deep and shallow water. These include molecular absorption and interference effects associated with shallow sources or receivers. A sloping bottom or special types of subbottom layers can also affect propagation, especially in shallow water.

2.4.1 Absorption

When sound energy is transmitted through water, a small portion is absorbed by water molecules. Absorption of sound by seawater increases with increasing frequency; energy loss is approximately proportional to the square of frequency. Absorption is also weakly influenced by water temperature. Furthermore, there is a relatively strong pressure dependence, with absorption coefficients being reduced with increasing depth. At frequencies >5 kHz, absorption causes significant (>2 dB) transmission loss if range is >10 km. At frequencies <1 kHz, absorption is not significant at ranges <40 km.

2.4.2 Shallow Source and Receiver Effects

When the source or receiver are very close to the surface, the surface reflection of the sound interacts strongly with direct sound radiation. The reflected sound is out of phase with the direct sound. If the source has strong tonal or narrow-bandwidth components, this phenomenon produces an interference pattern. It may be observed as range-dependent fluctuations in sound level at receiving locations along a horizontal radial line from the source. This phenomenon, the Lloyd mirror effect, is strongest with low-frequency tones and in calm sea conditions.

This effect occurs when range from source to receiver is long enough such that the direct and reflected path lengths are comparable. An interference field develops with alternating maxima and minima in received level. Beyond the interference zone, propagation loss is higher than normal when either the source or the receiver is close to the surface, that is, when their depths are less than• /4 for the dominant frequencies. With a shallow source, the source and its reflected image become effectively a dipole source with a vertical directionality (Urick 1983). In deep water, with both a shallow source and a shallow receiver, spreading loss may be as much as 40 log R, versus the 20 log R expected from spherical spreading. In shallow water, the shallow source dipole effect introduces an additional 10 log R spreading loss, increasing the loss from - 15 log R to - 25 log R. A similar interference effect occurs when the receiving location is within 1/4 wavelength of the surface. Thus, propagation from a shallow source to a shallow receiver in shallow water will show - 35 log R spreading loss. These types of effects occur for low frequency ship noise. Low frequency propeller noise is typically several decibels weaker when received near the surface than when received at depth.

2.4.3 Bottom Slope Effects

The slope of the bottom has a strong influence on sound transmission in shallow water. For transmission from a shallow region into deeper water, the increasing depth permits sound energy to spread out into a

larger volume than would have been available if depth had remained constant. This tends to result in a reduced sound level. On the other hand, a downward-sloping bottom causes decreasing angles of incidence of sound rays with the bottom and surface. This results in fewer reflections per kilometer, and thus less energy loss. For most bottom types, the reduction in reflection loss with increasing depth has a stronger influence than the increased water volume.
Hence, the net effect of a downward slope along the propagation path often is lower transmission loss.

An upward slope causes more surface and bottom reflections, and a steeper incidence angle for each reflection. Consequently, there is a net increase in loss rate as sound enters shallower water unless bottom loss is very low. As propagation continues upslope, there is a transition from multimode to single-mode propagation and a shift from 15 log R to 10 log R spreading loss. Although spreading loss is reduced, attenuation from bottom loss may be high because of the many reflections in shallow water. Eventually, depth is reduced to the point where modal transmission is not supported and the remaining sound energy is attenuated very rapidly.

2.5 Airborne Sound Transmission

Airborne sound transmission needs to be considered for two reasons. First, sound from some sources, especially aircraft, travels through air before entering water, and is attenuated along the airborne portion of the propagation path. Second, some marine mammals—pinnipeds and sea otters—commonly occur on land or ice, where they hear airborne sounds and emit aerial calls.

Sound from an omnidirectional source in an unbounded uniform atmosphere is attenuated only by spherical spreading (20 log R) and by absorption of sound energy by air molecules. However, sound from a source near the ground is affected by additional factors. The ground is usually nonrigid and permeable, and propagation near this surface is influenced by reflections and wave transmission along the surface. Interference between the direct, reflected, and ground wave paths causes fluctuations in received level and in frequency composition for near-ground transmission. Also, refraction caused by wind and temperature gradients produces shadow zones with poor sound transmission in the upwind direction, and often produces enhanced transmission downwind. When sound is transmitted from an elevated source such as an aircraft, the influence of gradient refraction and ground effects are greatly reduced, so for most airborne noise sources of concern in Glacier Bay the received level may be estimated by a simplified transmission loss relationship.

$L_r = L_s$ - 20 Log R – • R/1000

Where • is the atmospheric absorption loss in dB/km.

2.5.1 Atmospheric Absorption

Atmospheric absorption of sound at frequencies below 30 kHz is produced by oxygen and nitrogen molecules. The dominant mechanism is similar to the process acting underwater. The amount of absorption depends on frequency, temperature, relative humidity, and to a small degree atmospheric pressure. The physical relationships between these parameters and absorption are not easily expressed mathematically, but an empirical algorithm has been developed to compute absorption coefficients from these four parameters. At middle frequencies, sound absorption has more influence on sound transmission in the atmosphere than in the ocean. For example, at 1 kHz the underwater sound absorption coefficient is - 0.06 dB/km, whereas a typical value for in-air attenuation is - 4 dB/km. The absorption coefficient increases rapidly with frequency to - 130 dB/km at 10 kHz, depending on temperature and humidity. Hence, only low-frequency sound is transmitted well in air

2.6 Air-to-Water Transmission

Sound traveling from a source in air to a receiver underwater propagates in four ways: (1) via a direct refracted path; (2) via direct refracted paths that are reflected by the bottom; (3) via a lateral (surface-traveling) wave; and (4) via scattering from a rough sea surface. The types of propagation vary in importance depending on local conditions, depth of receiver, and bottom depth. The direct refracted path is important when the receiver is nearly under the aircraft. Snell's law predicts a critical angle of 13° from the vertical for the transmission of sound from air to water. Under calm sea conditions, sound is totally reflected at larger angles and does not enter the water. However, some airborne sound may penetrate water at angles >13° from the vertical when rough seas provide water surfaces at suitable angles.

Sound traveling from air to water along the direct refracted path passes through three phases: through air; across the air-water surface; and from the surface to the underwater receiver. To a first approximation, propagation loss in air can be described by simple spherical spreading—a 6 dB decrease per distance doubled. At the surface, the great difference in acoustic properties of air and water results in most acoustic energy being reflected. However, the sound pressure transmitted to the water is actually enhanced because of a pressure-doubling effect at the interface. Hence, sound pressure at the surface directly beneath the source is twice that expected in air at the same distance if there were no water surface. From the surface to the underwater receiver, sound propagation includes both geometrical spreading and the effects of the divergence of sound energy as it passes through the surface. This results in a complicated distribution of underwater sound pressure that depends on height of source, location of receiver, water depth, and temperature-salinity profile of the water column. Air-to-water sound propagation has been documented using wave theory. To estimate underwater sound levels produced by an airborne source over shallow water, an air-to-water sound transmission model has been developed (Richardson et al. 1995).

Model results are consistent with empirical data. In deep water, there are high transmission losses between a source in air and an underwater receiver distant from the subsource point. Underwater received levels away from the subsource point are higher in shallow than in deep water. This difference occurs because, in shallow water, sound is transmitted horizontally away from the subsource point by multiple reflections from the bottom and surface. This process is more efficient for hard bottom conditions. Even with a hard bottom, however, underwater noise diminishes more rapidly with increasing horizontal distance than does airborne noise. Consistent with this, under typical ambient noise conditions, an approaching aircraft can be heard in the air well before it is audible underwater.

2.7 Summary

Sound propagation in the sea has been the subject of intensive research. The open literature is voluminous, and there is additional unpublished and classified information. For specific applications, the information provided in this chapter should be augmented by a detailed review of relevant references.

Sound propagation research has made considerable progress in recent years. Field measurements of sound levels in relation to distance, frequency, and environmental parameters have been obtained in many areas and situations. Based on these data and on theoretical considerations, efficient computer models have been developed. Some models provide sufficient detail to account for many of the propagation processes occurring in the real world. However, most models are designed for specialized applications (often classified) and are not easily generalized for use in predicting potential noise impact ranges for anthropogenic sources. Fortunately, simple and general relationships can be used to make estimates of transmission loss for many sources and locations, both underwater and in air (Richardson et al.1995).

3.0 Zones of Influence

One method to assess the effects of man-made noise on marine mammals is to estimate the radii within which effects are expected. This “Zone of Influence” model was described in detail in Richardson *et al.* (1995) and is summarized here. Readers are directed to the original source for a more detailed description of the factors affecting zones of influence, and the variability therein.

There are at least four zones identified in which man-made noise can affect marine mammals. Those zones are:

1. *zone of audibility* – the area within which a sound is barely audible above background noise,
2. *zone of responsiveness* – the region within which an animal reacts to the sound either behaviorally of physiologically. This zone may or may not be smaller than the zone of audibility,
3. *zone of masking* – the region within which a man-made sound is strong enough to interfere with the detection of other sounds, such as communication or echolocation sounds,
4. *zone of hearing loss, discomfort, or injury* – the area within which the level of sound is high enough to cause discomfort or tissue damage to auditory or other systems.

Many assumptions must be made to predict radii of acoustic influence on marine mammals, and in many cases the data are not adequate to allow precise predictions. Local variables, including time, season, and location, will also affect radii of influence. While many factors prevent zones of influence from being exact predictors of the effects of noise to marine mammals, the model may be the best way to predict and mitigate the effects of man-made noise to marine mammals.

3.1 Zone of Audibility

The zone of audibility is the maximum possible radius of influence of a man-made noise on marine mammals. The radius of the zone of audibility is affected by many variables, including the source level and frequency, propagation loss, ambient noise, hearing sensitivity of the animal and individual variation.

Ambient noise greatly affects the zone of audibility. If the Signal to Noise Ratio (SNR, the difference between the received signal level and background noise level) is • 0 dB, the man-made noise may not be detected, and may not affect the animal.

Many man-made sounds are dominated by low frequency components. For a single source, dominated by low frequency components, the zone of audibility will vary greatly depending on the animals' abilities to hear low frequency sounds. Pinnipeds and odontocetes (toothed whales and dolphins) generally are not highly sensitive to low frequency sounds, while baleen whales are believed to be highly sensitive to low frequency sounds. Therefore, for a single source, the zone of audibility will vary greatly from species to species. If the ambient level is lower than the absolute threshold (the lowest sound level that can be detected) for the frequency in question, the zone of audibility will be determined not by the man-made sound, but by the sensitivity of the animal. The radius of influence will also vary depending on the sensitivity of the individual.

3.2 Zone of Responsiveness

The zone of responsiveness is the area around of source of man-made noise within which marine mammals of a given species show observable behavioral responses (Richardson *et al.* 1995). Many studies (e.g. Baker and Herman 1989, Frankel and Clark 1998, 2000, Bogaard *et al.* 1999, Todd *et al.* 1996) have documented behavioral changes in response to sound from human activities. However, types of behavioral responses and the distance at which reactions became evident varied widely, even for a particular species with the same human activity. Furthermore, behavioral differences are generally only detectible with sophisticated statistical techniques. Therefore, while the zone of responsiveness is a real phenomenon for many species and human activities, the radius is a statistical phenomenon: a few animals may respond at great distances, the majority may react when the source is closer, and a few may not respond until the source is very close or may not respond at all. To define the zone of responsiveness, it is necessary to define the proportion of animals expected to react, and the type of reaction that is expected.

The most obvious behavioral response to noise is an avoidance reaction. However, avoidance responses can be strong or weak. Animals may swim rapidly, directly away from a noise source, or may vary speed and direction from the source. Animals may even swim *toward* a source, for instance pinnipeds may move toward the water, or cetaceans in shallow water may move toward deeper water, even if the sound source is offshore. Other behavioral responses also may indicate disturbance. Pinnipeds on a beach may lift their heads or otherwise become alert, and cetaceans may change general activity state, resting or socializing whales may begin to travel. Other indications may not be easily detected by observation, the mean duration of surfacings and dives, blow rate, and blow intervals may change in response to sound. However, these responses are often only detectible with statistical tests. Those changes may, nevertheless, be useful as indicators of stress without any obvious avoidance response.

Biological factors can influence the responsiveness of animals to sound disturbance. Resting whales may be more apt to respond than animals that are socializing, feeding or mating (Richardson *et al.* 1985). Age and sex classes can also vary in their responsiveness. Immature or pregnant Steller sea lions at a haul-out site were more likely to enter the water when an airplane flew over than were territorial males or females with pups (Calkins 1979). Habitat differences may also influence responsiveness: walruses were more responsive to approaching boats when they were hauled out on ice than in the water (Fay 1984), and whales in shallow water or surrounded by ice may react more strongly to noise.

It is often difficult to determine appropriate criteria to measure the zone of responsiveness. Several methods of estimating the radii of influence have been suggested. One method is based on received sound levels: animals may react when the received sound level reaches or exceeds a specific level, in a specific bandwidth. One complicating factor of this method is determining which frequency band is appropriate. Response thresholds for broad bands are likely to be higher than for narrower bands which contain the most intense noise. For example, Richardson *et al*. (1990) determined that the response threshold for bowhead whales in the Beaufort Sea exposed to drilling and dredging sounds was approximately 115 dB re 1 • Pa on a broadband (20-1000 Hz) basis and approximately 110 dB re 1 • Pain the 1/3 octave band where industrial noise was most prominent. Another possible criterion is the Signal-to-Noise Ratio. A sound of given level may be more disturbing when the ambient level is low than when the ambient level is high. A third criterion possibility is that of distance from a sound source. Distance criteria are easy to define, implement and monitor for compliance. However, received sound level and distance are not perfectly correlated, and received sound level a given distance from a source will vary with time and location. Sound sources also vary, so received levels at a given distance will vary depending on the sound source (e.g. cruise ship v. private skiff). A further complication is the sensitivity of species in question. Distance criteria will be larger for species more sensitive to the dominant frequencies from a man-made sound source than for species less sensitive.

3.3 Zone of Masking

If noise is strong enough relative to a target signal, the signal will be "masked" and undetectable. In theory, each man-made sound source is surrounded by a Zone of Masking within which useful sounds are undetectable to marine mammals of a given species. The area where masking will occur is highly variable, and dependent upon all factors that affect the received levels of background noise and the sound signal.

Any man-made noise introduced into the marine environment will add to the background noise. This increase will interfere with an animal's ability to detect very weak signals. Therefore, the Zone of Audibility is also the largest potential Zone of Masking. For an animal close to a source of man-made noise, the noise level will be high and the animal would only be able to hear sounds from nearby animals, calls from animals further away would be weaker and may be undetectable. Thus, for animals that use low level sounds for communication such as baleen whales that may use weak, low-frequency sounds for communication (Payne and Webb 1971) the Zone of Masking will be larger than for animals that do not regularly use weak, low-frequency sounds. Short-distance communications are unlikely to be masked by distant sources of man-made noise. Therefore, the Zone of Masking is influenced not only by the level of the target sound, but also by its function. For a single species in a single situation, there may be multiple Zones of Masking, depending on the frequency, level, and function of the target sound.

There is some evidence that animals may have strategies to compensate for masking of useful sounds. This would be expected since natural background noise (wave noise, non-useful biological noise, etc.) can also mask useful sounds. Serrano and Terhune (2001) report that harp seals (*Pagophilus groenlandicus*) in the Gulf of St. Lawrence, Canada increased the number of elements per call as ambient calling rates (noise) within a breeding colony increased. The increase in the number of elements per call may be a strategy to avoid masking in a noisy environment and to maximize call detection over long distances.

3.4 Zone of Hearing Loss, Discomfort , and Injury

Prolonged or repeated exposures to high levels of airborne sound accelerates the normal process of gradual hearing loss in humans (Kryter 1985). This deterioration is a *permanent threshold shift* (PTS) in that sensitivity at some frequencies is permanently lowered; a higher level is required before it is detected. Besides PTS, temporary exposure to high noise levels can cause a *temporary threshold shift* (TTS) that can last anywhere from a few minutes to days. PTS can also develop from a brief exposure to an extremely high sound level, such as that from a nearby explosion.

There is little direct evidence that marine mammals suffer TTS or PTS, although it is assumed that the hearing sensitivity of marine mammals can be reduced at least temporarily by exposure to strong noises. Kastak *et al*. (1999) reported TTS in three species of pinnipeds after underwater exposure to noise. A harbor seal exposed to white noise with frequencies ranging from 100 Hz to 2,000 Hz at source levels between 60-75 dB for 20 – 22 min. experienced a threshold shift of approximately 4.8 dB, recovery to near baseline levels was reported within 24 hours of noise exposure (Kastak *et al*. 1999). Threshold shifts were similar for two California sea lions (*Zalophus californianus*)and a juvenile elephant seal (*Mirounga angustirostris*).

In humans, a chronic exposure of approximately 80 dB above threshold is required for PTS to develop. If the same follows for marine mammals hearing underwater, a chronic exposure to noise levels of ~120 db re 1• Pa, approximately 80 dB above absolute threshold, would be required for induce PTS in belugas (one of a few cetaceans for which absolute thresholds have been measured). For pinnipeds the exposure would probably be higher (~ 140 dB re 1 • Pa) given their higher absolute thresholds. While some marine mammals tolerate noise at ~120 dB re 1 • Pa, it is doubtful that marine mammals would remain in an area ensonified at 120 – 140 dB re 1 • Pa long enough to suffer TTS or PTS. Many of the loudest sources of man-made noise (e.g. supertankers or icebreakers) are themselves mobile, and are unlikely to ensonify a given area for long enough to induce TTS or PTS in marine mammals. However, while chronic exposure is unlikely, intermittent or explosive noise may be strong enough in some circumstances to induce TTS or PTS in marine mammals. In addition to inducing TTS or PTS, very strong explosive noise has the potential to cause tissue damage to auditory or other tissues. Todd *et al.* (1996) examined two dead humpback whales found near industrial explosive activities in Trinity Bay, Newfoundland. Both whales showed evidence of tissue damage consistent with extremely high noise levels, and it is likely that the noise contributed to the deaths of the whales. Besides damage to auditory tissues, extremely strong noise sources can cause damage to internal organs: respiratory cavities can be induced to resonate in response to strong underwater noise with the appropriate wavelengths.

3.5 Summary

Radii of influence of man-made noise to marine mammals are dependent upon numerous factors. The source level and spectral characteristics of the noise, the rate of attenuation of the noise, and ambient noise will all affect radii of influence. Attenuation and ambient noise are themselves dependent upon environmental characteristics, including water depth, water qualities, bottom characteristics, sea state, and many others. When considering masking, characteristics of the target signal also add to the variability in predicting radii. Predictions of radii are also variable due to the sensitivity, individual variation, and motivation of the marine mammals themselves. Much caution must be taken in developing and interpreting zones of influence. However, while many factors prevent zones of influence from being exact predictors of the effects of noise to marine mammals, the model may be the best way to predict and mitigate the effects from man-made noise.

4.0 Marine Mammal Hearing

Sound, unlike light and other stimuli, is transmitted very efficiently through water. Sounds from natural and man-made sources can often be heard for many kilometers, far beyond the range at which the stimuli would be detected visually either underwater or in air. Marine mammals probably use the characteristics of sound transmission to obtain information about their surroundings, including the presence of conspecifics and other marine mammals, and the presence of prey or predators. Concern has been raised that the multitude of man-made sounds introduced into the ocean may have deleterious effects to marine mammals.

Factors affecting marine mammal hearing

The hearing abilities of marine mammals (and other animals) are functions of the following (after Richardson et al. 1995):

1. Absolute hearing threshold – the level of sound that is barely audible in the absence of significant ambient noise.

2. Frequency and intensity discrimination – the ability to discriminate among sounds of different frequencies and intensities.

3. Localization – the ability to localize sound direction at the frequencies under consideration

4. Masking – the ability or inability to distinguish target sounds from ambient noise

5. Motivation – the psychological state of the animal may influence whether the sound is detected, and whether the animal reacts.

6. Individual variation – the variation between individuals in hearing sensitivity.

4.1 Absolute Threshold

Audiograms show the sensitivity of marine mammals to sounds of different frequencies. Audiograms are normally obtained using captive animals specially trained to respond when sounds become audible. In this way, the absolute threshold for various frequencies can be measured. Audiograms typically produce a U-shaped chart, with the best sensitivity (bottom of the U) in the middle frequencies, and decreasing sensitivity (higher intensity required for detection) at low and high frequencies. It is not known how well baleen whales follow this trend, their use of low frequency sound, and the anatomy of their auditory organs suggest that they may have good low frequency hearing. Audiograms have been obtained for seven species of toothed whales and seven species of pinnipeds. No audiograms have been collected for baleen whales. Of the marine mammals inhabiting Glacier Bay National Park and Preserve, audiograms have been obtained for only the killer whale and the harbor porpoise.

4.1.1 Odontocete Threshold

Odontocetes generally have very acute hearing at the middle frequencies, with lower sensitivity at low and high frequencies. The best frequencies for the seven species of odontocetes for which audiograms have been obtained ranged from ~8 to 90 kHz (Richardson et al. 1995). Hearing extends at least as low as 40 – 75 Hz in the beluga and the bottlenose dolphin, but their sensitivity at low frequencies appears to be low. By contrast, the sensitivity at high frequencies appears to be very good for most odontocetes, extending up to 80 – 150 kHz. The good high-frequency hearing is likely related to the use of high frequency sounds for echolocation.

4.1.2 Pinniped Threshold

Underwater audiograms have been obtained for four species of phocid (hair or true seals) including one for the harbor seal, which inhabits Glacier Bay National Park and Preserve waters, and for three species of otariid (sea lions and fur seals).

Phocids generally have flat audiograms from 1 kHz to 30 – 50 kHz with thresholds between 60 and 85 dB re 1 • Pa (Richardson et al. 1995). Little is known about pinniped hearing below 1 kHz, but for a single harbor seal sensitivity was 96 dB re 1 • Pa at 100 Hz (Kastak and Schusterman 1995). Sensitivity for most phocids remains good until about 60 kHz, after which sensitivity is poor (Richardson et al. 1995).

Underwater sensitivity at the high and low frequency ends of otariids is generally lower than for phocids, but there is little difference in the middle frequencies (Richardson et al. 1995). The high-frequency limit for most otariids appears to be about 36 – 40 kHz (Schusterman 1981), and sensitivity in the 100 – 1 kHz range appears to be lower than for phocids, based on the slopes of the audiograms that have been performed. Otariids that have been tested appear to have best sensitivity between 2 and 17 kHz (Moore and Schusterman 1987; Schusterman et al. 1972). Kastak and Schusterman (2002) recently reported that the auditory sensitivity of a free-diving California sea lion changed at depth. Hearing sensitivity generally worsened with depth, with significant interaction between depth and frequency. However, sensitivity at 50 m increased above 35 kHz compared to sensitivity at 10 m. Similar studies have not been conducted with phocids, but would help elucidate mechanisms of pinnipeds' underwater hearing.

Pinnipeds are amphibious and thus must also respond to airborne sounds. In-air audiograms have been obtained for two otariids and two phocids, including the harbor seal. Otariids apparently are more sensitive to airborne sounds and appear to detect higher frequency airborne sounds than phocids. The high frequency limit for otariids is similar to the underwater limit of 36 – 40 kHz, whereas for phocids, the upper limit appears to be around 20 kHz, considerably lower than the 60 kHz limit underwater. Sensitivity for both otariids and phocids deteriorates as the frequency goes below 2 kHz.

4.2.2 Frequency and Intensity Discrimination

The ability to differentiate between two signals of different frequency and intensity is important in detecting sound signals amidst background noise. This ability is also important for detecting calls from conspecifics, prey and predators.

Odontocetes apparently have very good frequency discrimination. Bottlenose dolphins can discriminate frequencies differing by 0.21 – 0.81% between 2 and 130 kHz (Thompson and Herman 1975). Pinnipeds have less precise frequency discrimination than odontocetes. Harbor seals were able to detect differences as small as 1.0 – 1.8% between 1 and 57 kHz (Møhl 1967, 1968).

Intensity discrimination may be important in detecting signals in the presence of noise. Odontocetes may be able to detect differences as small as 0.35 – 2.0 dB (Johnson 1971). Few data exist on the ability of pinnipeds to detect differences in intensity. Moore and Schusterman (1976) report that the California sea lion may be able to detect differences as small as 3 dB at 16 kHz.

4.2.3 Directional Hearing

The ability to localize sounds may be important for interactions among social marine mammals, and is undoubtedly important in prey detection by echolocation or by passive signal detection. Humans' ability to localize sounds depends on the interaural delay of sounds. Sound travels five times faster in water than in air, greatly reducing the ability to detect interaural delay. Bone conduction may also reduce the ability of terrestrial animals to localize sound underwater. In whales, the auditory organs are isolated from the skull, enhancing the ability to localize sound. Pinnipeds auditory structures are fused to the skull, which suggests a reduced ability to localize underwater sounds, but pinnipeds have other adaptations for hearing both in-air and underwater.

Odontocetes have very good ability to localize sound, as would be expected based on their echolocation abilities. Bottlenose dolphins are able to differentiate tones 2-3° off midline, and may have been able to detect clicks 0.7 – 0.9° off midline (Renaud and Popper 1975). Clicks are used for echolocation and should be more easily located than pure tones. These results were measured with the dolphin's head restrained. Head movement may increase the localization abilities of echolocating dolphins.

Pinnipeds have less precise abilities to localize sounds than odontocetes. A harbor seal was able to localize underwater tones ~ 6º apart (Møhl 1968b), and a California sea lion was able to localize underwater tones ~ 4º apart (Moore and Au 1975). The ability to localize tones is better in air than underwater. A harbor seal was able to localize clicks in air ~ 3º apart (Terhune 1974).

There is some indirect evidence that baleen whales have the ability to localize sounds at frequencies of a few hundreds, to tens of hertz (Richardson et al. 1995). Baleen whales sometimes orient and swim towards distant calling conspecifics (Watkins 1981; Tyack and Whitehead 1983), or swim directly away from predator calls (Malme et al. 1983) or industrial noise (Richardson et al. 1995).

4.3 Auditory Masking

Normal background noise (natural and man-made) may interfere with the ability of an animal to detect a sound signal. The amount by which a pure tone must exceed the background level in order to be audible is called the Critical Ratio (CR). CRs are generally measured for specific frequencies, since ability to detect sounds is dependent upon frequency. In general, CRs increase with increasing frequency.

4.3.1 Adaptations to Reduce Masking

Since natural noise can interfere with the ability to detect sounds, it would be expected that animals have developed strategies to reduce masking. Marine mammals that localize sounds reduce the effect of masking as a result of directional noises, that is masking is not as severe for important sounds that come from directions different than those of the noise. Masking of high frequency sounds in the bottlenose dolphin is strongly dependent upon the directionality of the sound and noise signals (Au and Moore 1984). In general, the masking effect of background noise is reduced if the noise either comes from a direction other than that of the target, or is omnidirectional (Richardson et al. 1995).

In order to reduce masking marine mammals may also shift the frequency of their calls from a "noisy" frequency band to one with less ambient noise (Lesage et al. 1999), increase the length of calls (Miller et al. 2000), change the duration of elements in calls (Norris 1999), increase the number of specific calls (Lesage et al. 1999) or elements within calls (Serrano and Terhune 2001).

4.4 Individual Variation and Motivation

In addition to the physical factors that influence marine mammal hearing, individual variation in hearing abilities and differences in motivation will influence the effects of sound to marine mammals. Ketten et al. (1995) compared hearing abilities of a long-term captive dolphin, one juvenile, and two young adult dolphins. The older dolphin showed hearing loss consistent with age related hearing loss in humans. The older dolphin showed a shift in high frequency sensitivity from normal threshold levels up to 165 kHz to no functional hearing above 60 kHz at his death at age 28. The conclusion was that the hearing loss was attributable only to age-related changes in the ear.

Reactions of marine mammals to sounds vary considerably. Some humpbacks show little or no reaction to vessels within distances that other humpbacks have shown obvious reactions. Krieger and Wing (1984, 1986) determined that humpbacks are less likely to react to vessels when they are actively feeding than when resting or engaged in other activities. Humpback pods with calves, or small pods, were more likely to react to vessels than were larger pods or pods without calves present (Bauer et al. 1993). Thus, the motivation (behavioral state, whether sound is perceived as a threat) will affect how or whether marine mammals will react to sound.

4.5 Baleen Whale Hearing

There are no audiograms for baleen whales, so all information about hearing in baleen whales is based on behavioral observations, anatomical evidence, and extrapolations from other marine mammal hearing characteristics. Field observations of the responsiveness of baleen whales to sounds can set an upper bound for detection thresholds. However, it is not possible to determine if sounds at lower levels than those that elicited a response were detected but did not elicit an overt response or were undetected by the animal. Humpback whales reacted to calls from other humpbacks at levels as low as 102 dB re 1 • Pa,and bowhead whales fled from an approaching boat when the noise level was 90 dB re 1 • Pa(Frankel et al. 1995; Richardson and Greene 1993).

Baleen whales are probably able to hear low frequency sounds, including infrasounds (< 20 Hz). Baleen whales react to sounds from conspecifics that range from 20 Hz (fin whales) to 550 Hz (humpback whales) (Watkins 1981; Frankel et al. 1995). Humpback, gray and bowhead whales all react to airgun pulses and underwater playbacks of low frequency (50 – 500 Hz) man-made sounds (Richardson et al. 1995). Anatomical evidence also suggests that baleen whales are adapted to hear low frequency sounds (Ketten 1998). The upper bounds of baleen whale hearing are not as high as odontocetes. Humpback whales reacted to sonar signals at 3.1 – 3.6 kHz and broadband clinkers centered around 4 kHz (Lien et al. 1990, 1992; Maybaum 1993). Watkins (1986) reported that baleen whales react to sonar sounds up to 28 kHz, but not to sounds 36 kHz and above.

4.6 Marine Mammal Sounds

The frequencies of sounds produced by marine mammals identify at least some of the frequencies important to these species. Marine mammals probably use sounds they create to obtain much information about their environment, including information about the presence of danger, food, a conspecific or other animal, and to transmit information about their own position, identity, and territorial or reproductive status (Richardson et al. 1995). While the sounds created by marine mammals are a good indication of frequencies important to those species, it is likely that higher and lower frequencies are also important.

4.6.1 Mysticete Sounds

Since baleen whales have rarely been held in captivity, sounds created by baleen whales have generally been recorded in the wild. Most baleen whale sounds are dominated by low frequencies, generally below 1 kHz, although a few recordings of clicks with dominant frequencies from 16 to 25 kHz have been recorded near minke, fin and blue whales (Beamish and Mitchell 1973; Thompson et al. 1979; Beamish 1979). It is thought these high frequency sounds may have been from odontocetes in the area, or recording artifacts (Richardson et al. 1995).

Humpback whales produce stereotyped songs associated with reproduction on low-latitude wintering grounds (Tyack 1981). Songs have occasionally been recorded on the high-latitude summer feeding grounds (Mattila et al. 1987; McSweeney et al. 1989; Gabriele et al. 2001), in late summer or early fall. Gabriele et al. (2001) suggest that the increase in song frequency in fall may correspond with the beginning of hormonal activity in male humpbacks associated with the migration to the wintering grounds. Humpback whale song elements range from • 20 Hz to 4 or 8 kHz, estimated source levels range from 144 to 174 dB re 1• Pa (Thompson et al. 1979).

On the summer feeding grounds humpbacks produce sounds associated with feeding behavior (Jurasz and Jurasz 1979; Cerchio and Dahlheim 2001). These calls ranged from 236 – 1219 Hz (Cerchio and Dahlheim 2001). It is suggested that these calls may serve to manipulate prey distribution (scaring fish into tighter groups) and as assembly calls, but not to coordinate feeding (Baker 1985).

Humpbacks also produce sounds on the wintering grounds associated with agonistic behavior in social groups. The sounds extend from 50 Hz to • 10 kHz. These sounds may elicit response from humpbacks up to 9 km away (Tyack and Whitehead 1983).

4.6.2 Odontocete Sounds

Odontocetes produce three broad types of sounds, tonal whistles, short duration pulsed sounds, and less distinct pulsed sounds such as cries, grunts and barks. Odontocetes that produce whistles tend to be social, gathering in large groups of up to thousands of individuals, while non-whistling odontocetes tend to be non-social or gather in small groups of a few individuals (Tyack 1986; Herman and Tavolga 1980).

Most odontocete's whistles are narrow-band sounds. Whistles typically have most of their energy below 20 kHz and can vary greatly in frequency structure. Some odontocetes may use special, unique whistles as "signature calls" that may carry some information about the sender. Whistles may also serve to coordinate activity such as feeding in large, dispersed groups (Norris and Dohl 1980; Würsig and Würsig 1980).

Clicks and pulsed sounds are typically short (50 – 200 • s) bursts of sound that can range from 0.1 – 200 kHz (Watkins 1980; Santoro et al. 1989). Source levels of sperm whale clicks can be near 180 dB re 1 • Pa-m (Watkins 1980). Clicks have been demonstrated to be used for echolocation in several species of odontocetes, and numerous other species produce echolocation type sounds although they have not been proved to echolocate. Echolocating odontocetes produce forward directional pulsed sounds of high frequency (12 – 150 kHz), short duration (50 – 200 • s), high intensity (up to 220 – 230 dB re 1 • Pa-m) sounds.

4.6.3 Phocid Sounds

Phocid seals are diverse in their behavior and habitat use, some spend almost all their time in water or hauled out on ice. Others haul out regularly on land. Most phocid seal calls seem to be associated with mating, mother-pup associations or territoriality. Underwater calls may be less important for species that perform those activities on land. Some phocids produce sounds that propagate for long distances, and others produce faint sounds that probably do not propagate far. Phocids probably hear sounds up to approx. 60 kHz underwater, and most calls are made between 90 Hz and 16 kHz (Richardson et al. 1995).

Harbor seals spend considerable time hauled out on land, although much social behavior occurs underwater as well. Males produce repeated call trains of low frequency (<4 kHz) underwater pulses including roars, grunts, and creaks (Hanggi and Schusterman 1994). Calls from pups are individually distinct and broadcast simultaneously in-air and underwater when the pups head is in the air. Females use calls from their pups both in-air and underwater to recognize and maintain contact with their pups. Pup calls in-air are centered around 350 Hz, (Ralls et al. 1985) while underwater calls are shifted to higher frequencies (Richardson et al. 1995).

4.6.4 Otariid Sounds

Sea lions and fur seals spend a great deal of time hauled out on land. They defend territories, mate, and give birth on traditional terrestrial rookeries. In-air vocalizations are used to defend territories, attract females, and establish and maintain mother-pup bonds.

No information exists on the frequency composition or source levels of Steller sea lion calls. Only California sea lion calls have been recorded and analyzed, and are thought to be generally consistent with those of Steller sea lions. California sea lion males bark incessantly while defending territories on rookeries. Barks have most energy <1 kHz. Females bark at intruders into their territory, squeal, belch and growl. Females exchange calls with new pups for several hours after birth. Mothers and pups are then able to recognize one another by their calls (Trillmich 1981). Female belches and growls have most energy between 0.25 – 4 kHz, female – pup attraction calls are 1 – 2 kHz and the pup's bleat is at 0.25 – 6 kHz (Peterson and Bartholomew 1969). Male Steller sea lions roar and hiss to defend territories on rookeries, and females defend birthing territories with barks and growls. Females and pups exchange vocal signals soon after birth, the calls may function in mother – pup recognition.

Underwater sounds of California sea lions are generally associated with social situations (Schusterman et al. 1966). Most underwater sounds are barks that are produced while the head is above the surface. Most of the energy is at frequencies below 2 kHz, and is similar in water and air (Schevill et al. 1963). When submerged, California sea lions produce barks, whinny and buzzing sounds, and click trains (Schusterman et al. 1966). Steller sea lions are said to produce clicks, growls, snorts and bleats underwater (Poulter 1968).

4.6.5 Sea Otter Sounds

Sea otters spend much of their time in water, but underwater sounds have not been studied. Airborne sounds of adult sea otters include: whines, whistles, growls, cooing, chuckles, snarls, and screams (Kenyon 1981). Otters may also produce sounds by vigorously kicking and splashing while at the surface (Calkins and Lent 1975). Calls between mothers and pups appear to be important for maintaining contact (Sandegren et al. 1973). Most of the energy in mother and pup calls is between 3 – 5 kHz.

5.0 UNDERWATER NOISE ACOUSTICS ENVIRONMENT

The ambient underwater noise in Glacier Bay results from both natural and man-made sources. The natural sources are primarily splash noise from wind-generated waves, and turbulence noise from high tidal currents in restricted channels. Other sources of natural noise that are unique to Glacier Bay are found in Sitakaday Narrows and in upper-bay waters that are near the glaciers. The noise in Sitakaday Narrows is produced by current interaction with the bottom - that results in turbulence noise and impact noise caused by the movement of small rocks and boulders as they are tumbled down bay by the strong tidal flow. In the upper bay, and in particular, Queen Inlet, glaciers advancing intermittently down mountain slopes produce strong low frequency underwater rumbles resembling thunder. These sounds can be heard as they propagate out into the bay as far as the Marble Islands, and occasionally, in quiet background conditions, in Bartlett Cove.

Man-made components of ambient noise are primarily caused by water transportation activities. Cruise ships are the loudest sources but tour boats, charter boats, private skiffs, and even airplanes contribute to the underwater noise levels in areas near Bartlett Cove and other areas where park visitors may be concentrated. Vessel noise is considered part of the ambient noise if no nearby source can be recognized. The following discussion presents details concerning the natural and man-made components of Glacier Bay underwater noise collected in the 1980s. Readers are encouraged to read the previous sections "Acoustic Concepts and Terminology", "Sound Propagation", "Zones of Influence", and "Marine Mammal Hearing" before reading this section. It must be noted that there are more current data for the underwater acoustics environment in Glacier Bay, however, those data are not widely available. Obtaining those data will allow a more complete description of the underwater environment in Glacier Bay and provide a better basis for comparisons of the effects of the alternatives presented within this EIS.

5.1 Ambient Noise Levels

Ambient noise has both long-term and transient properties. The long-term properties are described in terms of their average (mean rms) overall sound level, temporal statistics (transient level fluctuations in time) and frequency composition. Ambient noise data are generally measured at a single point for a long period (several hours or days). . The fluctuations in sound energy that normally occur over the sampling period are generally averaged to an equivalent sound level (L_{eq}), which is the constant rms sound level that would provide the same acoustic energy as the actual signal over the same period. The range in amplitude of the fluctuating sound level is described statistically by the percentage of time that the "instantaneous" rms level is above or below selected values, typically 5%, 50% and 95% of the total range observed during the measurement period. The frequency composition is usually measured as a 1/3 octave band using the same measurement period as used in determining the L_{eq}. When signals with strong tonal components are present, a narrow band analysis may be used to obtain better frequency definition since most of the energy is contained in a narrow band that includes the tonal frequency. The 1/3 octave band analysis is used for broadband signals because it provides a better correspondence to the hearing sensitivity of humans (and other mammals).

Acoustic measurements in Glacier Bay have provided data to compare the ambient sound levels in various parts of the bay with archival data obtained in open water areas to determine if Glacier Bay is more or less "noisy" than open water areas nearby. Data reported by Wenz (1982) and Urick (1983) are compared with data obtained by Miles and Malme (1983) in Bartlett Cove as shown in Fig. 1. The Bartlett Cove data were obtained for conditions with very light winds, so the variation in sound level over the two

8-hr measurement periods was due primarily to boat and ship traffic, rather than differing environmental conditions. The mean sound level from boat and ship traffic in Bartlett Cove corresponds to a Sea State 4 (wind speed of about 20 kts) in open water.

It is also necessary to consider the temporal characteristics of ambient noise. The long term averages discussed previously convey the impression that sound levels under water are nearly constant. This is not the case in Bartlett Cove as shown in Fig. 2, taken from a graphic level recording sequence obtained over two 10-minute periods in Bartlett Cove (Miles and Malme 1982). The record shows the fluctuations in overall sound levels due to humpback whale vocalizations, ship arrivals and departures, and fishing boat movements. The level of the whale vocalizations is much higher (at the measurement position) than the departure of the cruise ship Statendam as it begins to travel up bay.

There is a wide variation in ambient noise for other sites in the bay, as can be seen in Figs.3A and 3B. Station 17 near North Marble Island shows sound levels lower than Sea State 0 (calm winds, smooth seas) at frequencies above 250 Hz. The low frequency noise levels seen in Figs. 3A and 3B are from either distant ships or glacier motion. Intermediate levels of noise are seen in the spectrum obtained in Queen Inlet. The narrow band peaks in this spectrum are caused by glacier rumbles. The spectrum obtained near Muir Glacier is dominated by the noise of out-gassing from the glacial ice nearby. The high frequency sounds are higher than would be obtained by wind and wave noise at Sea State 6 (wind speed about 30 kts).

5.2 Description of Noise Range for Each Vessel Class

The man-made component of ambient noise is produced primarily by ship and boat movements. It is possible to categorize the classes of vessels using the bay by type or application. However, on analyzing the acoustic output of vessels of the same type, a wide variation is often found. As a result, only two general classifications, cruise ships, and other miscellaneous boats, have been used. This may be modified when acoustic data from additional vessels become available. Figure 4 shows the source level spectra for the range of sound levels produced by 6 representative cruise ships for which data are available. For comparison, the source levels of a range of smaller vessels, representative of the types that use the bay, are also shown. These spectra were obtained by estimating transmission loss (TL) for received levels reported by Malme et.al. (1982). The received energy levels for each 1/3 octave band were summed to obtain an overall source level (L_s) for each vessel. The average source level for the cruise ships is about 179 dB, with 9 dB variation between the maximum and minimum overall source levels. The average source level for the smaller vessels is 164 dB with variation of 10 dB. The difference in average source levels between the cruise ships and the smaller vessels is about 15 dB.

In order to estimate the assumed zone of responsiveness (Sec. 3.2.4.2), or the range at which the overall radiated sound level from these vessels approaches the 130 dB disturbance criterion, it is necessary to review the Glacier Bay TL data reported by Malme et al. (1982). The data are summarized for 200 Hz in Fig. 5. The TL measured for Station 41, at the bay entrance, was selected for a whale waters location. The estimated ranges are shown in Table 5-1.

TABLE 5-1: NOISE RANGES BY VESSEL

Vessel Class	L_s, dB re 1 µPa @ 1 m	Criterion, dB re 1 µPa	Required TL, dB	Minimum Range, m
Cruise Ships	179	130	49	600
Tour, fishing, sport, misc.	164	130	34	50

The TL data reported by Malme *et al*. (1982) at six sites in Glacier Bay included a range of 100 Hz - 16,000 Hz. In this case 200 Hz was selected as a representative frequency, as sounds from cruise ship are generally low frequency. Further TL analyses will be made to include TL values for all frequencies at selected sites reported by Malme *et al*. (1982) to provide a more optimum match with the spectra of the cruise ships. Additional analysis will also be made using an expanded ship database including all the vessels that visited the park during the 2001 season to provide a more detailed and relevant analysis for ships in Glacier Bay.

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